Earth Surface and Interior Structure

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- Note: John LaBrecque (Lead) and Carol Raymond (Lead)

Earth Surface and Interior Structure

Critical Science Questions

Existing Roadmaps: *Given what we have heard about UAV potential, what of the 2007-2015 Roadmap goals could be addressed from a SUBORBITAL platform?*

The listed measurement goals are cross-cutting to the six high-priority science themes within the Solid Earth Program

- Surface deformation
- High-resolution topography
- Variability of Earth's magnetic field
- Variability of Earth's gravity field
- Imaging Spectroscopy of Earth's changing surface
- Geodetic reference frame

Other Roadmap Possibilities: *Are there other things that should be in the Roadmap now that we see what is possible?*

- Sampling of the spatial wavelengths between those sampled by surface and spaceborne vantage points, to better understand crust-mantle interactions (spatial resolution ~ observation altitude)

- Sampling of highly time-variable phenomena inaccessible from space (surface deformation, gravity changes), such as magma dynamics, transient slip on fault (aseismic slip, post-seismic relaxation). Each improvement in measurement of transient tectonic processes yields new information about the temporal complexity of these processes

Phasing Observations: *How would we phase the critical observations in our Earth Science focus area that are most suitable for the suborbital platform realm?*

- Comprehensive geophysical hazard observatory
  - surface deformation – topography and surface change
  - high–precision gravity
  - vector magnetometry
  - passive and active EM
  - imaging spectroscopy, including thermal IR

- Ice Sheet thickness

- Geodetic reference frame improvement

Earth Surface and Interior Structure – Surface Deformation

<u>Critical Observation</u>: Surface Deformation

<u>Observation / Measurement Definition</u>: Describe the phenomenon you want to observe. Describe what you need to measure.

- The geophysical processes associated with natural hazards such as earthquakes, landslide, and volcanoes occur over a wide range of temporal and spatial scales, and express themselves as deformations in the Earth's crust. The desired accuracy in surface deformation measurement may range from a millimeter to a decimeter.
- Present observational capabilities include sampling quickly varying surface change using *in situ* GPS methods, or observing fine spatial scale changes using interferometric synthetic aperture radar (InSAR).
- Generate fine resolution, accurate observations of crustal deformation resulting from natural hazards at hourly intervals.
  - Driven by slow plate motions, rapid injection of magma into the plumbing system of a volcano can lead to explosive eruptions over hours to days. Measurements from this system will lead to better models of the internal plumbing and magma flow within a volcano.
  - Steady slip along a fault in the crust can lead to sudden, major earthquakes and days of continuing slip. Using measurements from this system a better understanding and assessment of the rate of slip and rebound surrounding a seismic event can be obtained.
  - Gradual movement of hillsides as a result of heavy rainfalls may eventually lead to catastrophic landslides. Accurate measurements of surface deformation over areas prone to landslide will assist in assessment of the process.
- Additional science studies include rapidly moving glaciers and volumetric decorrelation studies in ice and vegetation.

Explicitly state how this observation and measurement supports this Earth Science focus area.

- From ESE Solid Earth Roadmap “Provide Crustal structure, high temporal resolution, regional deformation processes for increased predictability of earthquake and volcanic activity”

Earth Surface and Interior Structure – Surface Deformation

Explicitly state the advantage of using a suborbital platform for this measurement.

- Airborne InSAR can contribute to local measurements of rapidly evolving surfaces with temporal and spatial scales not supported by existing or planned spaceborne assets, which are not likely to exist for at least a decade or more.
- The temporal and spatial scales provided by the suborbital system would require an advanced spaceborne system such as a constellation of LEO or MEO spacecraft, or three GEO SARs.
- The suborbital platform provides this capability but for limited geographic areas.

Identify other cross-cutting areas impacted by this observation.

- Can monitor subsurface aquifer discharge/recharge
- Biomass and vegetation structure

<u>Observation / Measurement System Requirements</u>: Describe how you want to observe or measure the phenomena. Consider the following:

Instrument / Payload characteristics (type, weight, volume, environmental considerations, and access such as sampling or viewing ports)

- Use repeat pass radar interferometry with electronically scanned antenna,or single-pass InSAR using two UAVs (formation flying).
- Want very stable flight lines while staying within a desired flight tube of 10 m.
- Operate in a variety of weather conditions
- Operate from conventional airports
- Operate above 12,000 meters to avoid commercial traffic and reduce turbulence
- Able to maintain a flight path with positional accuracy of ±5 meters
- Minimum range of 2000 nautical miles (We should specify min time duration as well)
- Minimum payload capacity of 300 kilograms
- Minimum payload volume of 1 cubic meter
- Minimum 2,000 watts of DC power available for the payload (is this enough?)
- Support over-the-horizon up/downlink
- Able to mount an external, side-looking, active array antenna (0.5m by 2.0m) without obstruction

Earth Surface and Interior Structure – Surface Deformation

Mass Estimate

Radar Subsystem	**Baseline Configuration** (do you mean repeat-pass?)	**Interferometer Option** (specify baseline and UAV platform the can support this)	**Dual Frequency Option** (Specify frequencies)
Antenna	39.1	78.2	156.4
RF Electronics	8.2	11.8	20.9
Digital Subsystem	24.5	27.3	50
PDU, INU, etc…	100.7	100.7	100.7
Racks and Misc.	40.9	45.4	63.6
Radar Total	213.4	263.4	391.6

Power Estimates

Radar Subsystem	**Baseline Configuration**	**Interferometer Option**	**Dual Frequency Option**
Antenna	240	480	960
RF Electronics	194.4	216.8	411.6
Digital Subsystem	516	566	1014
PDU, INU, etc…	304	304	304
Radar Total	1254.4	1566.8	2689.6

Earth Surface and Interior Structure – Surface Deformation

Flight characteristics (location, altitude, endurance, season, frequency). Discuss number of platforms, formation flying, or other special flight characteristics.

- Flight lines: Straight and level lines at 13.7Km nominal altitude
- Location: Worldwide
- Seasons: All
- Persistent Observations: days to weeks

Communication needs such as real-time data or instrument control

- Low data rate over the horizon uplink/downlink capability. Broadband downlink is desirable.

Earth Surface and Interior Structure – Surface Deformation

<u>Mission Concept</u>: Describe in as much detail as possible the measurement approach:

Provide a narrative describing a "day-in-the-life" of the mission.

- Fly long-level flight lines at 13,700 m in a grid pattern 50-100 km on a side (~ 3 lines in each direction over the target of interest (earthquake fault, volcano, vulnerable slopes). Data is collected and stored in a continuous mode. Refly the survey at delta-time of hours to days to weeks.

Develop a diagram showing flight profile or maneuvers in time, space and/or geographic coordinates.

(no input)

Identify any special or unique platform or mission issues

- Single Pass Interferometry for Topography

- A baseline metrology system is needed to measure the 3 dimensional location of the antenna phase center with an accuracy of a fraction of a millimeter. This is done with a combination of INU data and a camera and ranger to each antenna.
  - INU provides accurate attitude information
  - Camera and ranger data provide accurate state vectors between a fixed point on the fuselage and a point on the antenna structure
  - Combination allows determination of the interferometric baseline

Summarize the key elements of the mission concept for this measurement.

1. High altitude UAV able to fly a stable flight line along a desired flight path within 10 m diameter tube.
1. Electronically scanned antennas to fix the antenna beam in a desired direction. This will allow for compensating for yaw angle differences between flight lines.
1. Light weight and autonomously operating radar instrument.

Earth Surface and Interior Structure – Ice Sheets

<u>Critical Observation</u>: Ice Sheet Thickness and Surface Deformation

<u>Observation / Measurement Definition</u>: Describe the phenomenon you want to observe. Describe what you need to measure.

- The accurate measurement ice sheet thickness is important for the study of glaciers and global warming.
- Present observational capabilities include *in situ* low frequency radar sounding and , airborne observation using interferometric synthetic aperture radar (InSAR).
- Generate fine resolution, accurate observations of ice thickness and crustal deformation of underlying surfaces due to ice sheet loading and earth internal activities such as earthquakes.

Explicitly state how this observation and measurement supports this Earth Science focus area.

- This measurement can provide high spatial and temporal resolution of ice sheet thickness and the underlying surface deformation.

Explicitly state the advantage of using a suborbital platform for this measurement.

- Low altitude ad hoc network of sparse UAVs, each carrying a synchronized VHF or UHF TR module, can generate a very high resolution 3-D map of the ice sheet structure under its footprint and along its flight path.

Identify other cross-cutting areas impacted by this observation.

- Same idea can be implemented to measure tree structures and under canopy ground deformation.

Earth Surface and Interior Structure – Ice Sheets

<u>Observation / Measurement System Requirements</u>: Describe how you want to observe or measure the phenomena. Consider the following:

Instrument / Payload characteristics (type, weight, volume, environmental considerations, and access such as sampling or viewing ports)

1) Use many (> 50) microaerial vehicles in an ad hoc formation flying (footprint ~ 100 diameter)
1) Require relative position of UAVs with respect to a coordinate system to within a fraction of a wavelength. (need differential GPS)
1) Need a communication link (to satellites, nearby base-stations, or a larger UAV flying over the MAVs)
1) Operate from conventional airports
1) Operate at an altitude of about 200 meters or less to achieve high resolution and for S/N consideration.
1) Minimum range of 200 Km (to get a raster image of 10KmX 2Km)
1) Minimum payload capacity of 3 kilograms
1) Minimum payload volume of 10^{-3} cubic meter
1) Minimum 10 watts of DC power available for the payload
1) Support over-the-horizon up/downlink

Flight characteristics (location, altitude, endurance, season, frequency). Discuss number of platforms, formation flying, or other special flight characteristics.

- Flight lines: Straight and level lines at 150 m nominal altitude
- Persistent Observations: days to weeks

Communication needs such as real-time data or instrument control

- Relatively high data rate over the horizon uplink/downlink capability.

<u>Mission Concept</u>: Describe in as much detail as possible the measurement approach:

Provide a narrative describing a "day-in-the-life" of the mission.

- Parallel lines to create a raster image

Develop a diagram showing flight profile or maneuvers in time, space and/or geographic coordinates. *(no input)*

Identify any special or unique platform or mission issues *(no input)*

Summarize the key elements of the mission concept for this measurement.

- Low altitude formation flying of a large number of very small UAVs .

Earth Surface and Interior Structure – Imaging Spectroscopy

Critical Observation: Surface solid earth composition, change, related atmospheric phenomena

Observation / Measurement Definition: Describe the phenomenon you want to observe. Describe what you need to measure.

- Surface composition, change, water vapor and sulfur dioxide in space and time.

Explicitly state how this observation and measurement supports this Earth Science focus area.

- Called out in SESWG
- Measures the composition and change in the solid earth at the Surface atmosphere interface.
- Measures accurate precise 3D water vapor for GPS based derivations.
- Measures 3 D SO2 and other phenomena associated with active volcanology WITH TWO BREAD BOXES.
- Measures earthquake fault optical spectroscopy properties before and after

Explicitly state the advantage of using a suborbital platform for this measurement.

- Need rapid response.
- Need hourly sampling over the course of a day.
- Need spectra, high spatial resolution, and angular acquisitions.

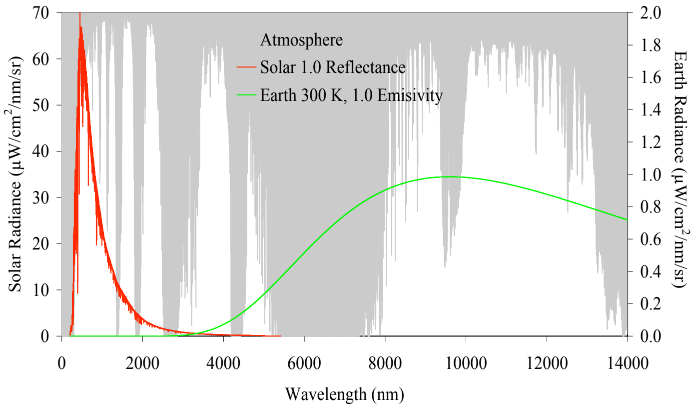
Identify other cross-cutting areas impacted by this observation.

- Carbon, Ecology, Atmosphere, etc.

Earth Surface and Interior Structure – Imaging Spectroscopy

<u>Observation / Measurement System Requirements</u>: Describe how you want to observe or measure the phenomena. Consider the following:

Instrument / Payload characteristics (type, weight, volume, environmental considerations, and access such as sampling or viewing ports)



- Measure the optical spectrum from 400 to 2500 nm at <=10nm as images 36 degree swath with 1 milliradian sampling.
- Measured 7000 to 13000 nm at <=40nm as images 36 degree FOV and 2 milliradian sampling.
- Measure both with point angle range to all tomography
- Flight Characteristics over site 12 to 24 hours, over days to months, altitude 45kft
- Real-time data required

- Mass: 50kg, Power: 200W, Volume 0.5m3, down looking port.

Flight characteristics (location, altitude, endurance, season, frequency). Discuss number of platforms, formation flying, or other special flight characteristics.

- Global response
- Altitude 45kft

Communication needs such as real-time data or instrument control

- Telemetry and quicklook

Earth Surface and Interior Structure – Imaging Spectroscopy

<u>Mission Concept</u>: Describe in as much detail as possible the measurement approach:

Provide a narrative describing a "day-in-the-life" of the mission.

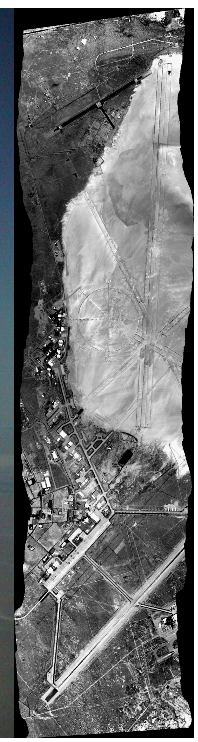
- Mode 1: Collect baseline and periodic monitoring
- Mode 2: Begin acquisition suite based on hypothesized hazard
- Mode 3: Respond after phenomena (volcanic eruption, earthquake, flood, etc)

Develop a diagram showing flight profile or maneuvers in time, space and/or geographic coordinates.
(no input)

Identify any special or unique platform or mission issues
(no input)

Summarize the key elements of the mission concept for this measurement.

- Measure spectra as images in rapid response and in monitoring mode.



Earth Surface and Interior Structure – LIDAR

<u>Critical Observation</u>: Continuously operating, targeted, high-resolution topographic mapping and topographic change-detection of the ground surface, including where covered by vegetation

- All-terrain topographic change detection by repeat mapping compliments interferometric SAR measurements of sub-cm to decimeter surface (e.g., observe decimeter to tens of meter near-field surface deformation in the vicinity of ruptured faults and inflating volcanoes to understand earthquake and magmatic processes; observe decimeter to hundreds of meters topographic change associated with landslides, volcanic eruptions and flows, coastal and fluvial erosion and sediment redistribution)

<u>Observation / Measurement Definition</u>: Describe the phenomenon you want to observe. Describe what you need to measure.

- Targeted local to regional mapping, with global access, at 1-m resolution and 0.1-m vertical accuracy (referenced to a globally defined absolute datum)
- Repeat frequency of hours to years depending on the rate of topographic change

Explicitly state how this observation and measurement supports this Earth Science focus area.

- This is the long term (10 to 25 year) goal for high-resolution topography mapping identified in Living on a Restless Planet, the report of the NASA Solid Earth Science Working Group.

Explicitly state the advantage of using a suborbital platform for this measurement.

- Targets of highest priority are narrow, long, quasi-linear features (e.g. fault zones, coastal zones) amenable to targeted mapping or point features (e.g. volcanoes) amenable to station-keeping monitoring
- Required temporal and spatial coverage is not achievable from near-space orbital systems (LEO/MEO) with technology likely to be available in the next 10 years
- Required spatial resolution and vertical accuracy is not achievable from far-space orbital systems (L1/L2,HEO/GEO) with technology likely to be available in the next 10 years

Identify other cross-cutting areas impacted by this observation.

- High-resolution elevation mapping and change detection are equally applicable to measurements of inland water storage and discharge (from changes in water stage, slope, and extent), ice sheet mass balance, glacier and ice stream dynamics, snow pack depth, sea ice thickness, vegetation cover attributes (e.g. biomass, forest fire fuel quantity and quality), and solid planet and moon surface topography

Earth Surface and Interior Structure – LIDAR

<u>Observation / Measurement System Requirements</u>: Describe how you want to observe or measure the phenomena. Consider the following:

Instrument / Payload characteristics (type, weight, volume, environmental considerations, and access such as sampling or viewing ports)

- Geodetic imaging lidar (i.e., scanning laser altimeter) integrating time-of-flight ranging of pulsed or encoded continuous-wave laser light, precision trajectory determination, and precision attitude determination

  - Mass 30 kg (1/3 COTS)
  - Average power draw 200 W (1/5 COTS)
  - Volume 40 x 40 x 40 cm (1/2 COTS)
  - 1.5 million range observations per sec (10x COTS)
    - (3 km swath width, 5 returns per 1 m pixel, & 100 m/sec ground speed)
  - 20 km flight altitude (10x COTS)
    - (near-nadir ±4° scan to achieve swath while preserving water returns and reducing pointing-induced range errors)
  - Post-flight knowledge of the aircraft flight path:
    - <5 cm radial (= COTS) over 200 km GPS baselines (10x COTS)
  - Post-flight knowledge of sensor attitude: 5 arc sec per axis (20x COTS)

  - COTS system used for comparison is the Optech ALTM 3100 (a representative state-of-the-art commercial system)

- The above is a representative instrument configuration. Trades can be made between flight altitude, swath width, data density, off-nadir scan angle, vertical accuracy and attitude knowledge. ±4° scan angle is an upper limit to acquire returns from smooth water surfaces which act as specular reflectors. Flight altitudes above commercially controlled airspace are desirable for operational efficiency in following and later repeating specific flight lines.

Flight characteristics (location, altitude, endurance, season, frequency). Discuss number of platforms, formation flying, or other special flight characteristics.

- Single platform operating at 20±2 km altitude and 100±20 m/sec ground speed targeting altimeter swath on pre-programmed ground track with cross-track accuracy of 150 m (achieved by combination of real-time navigation and sensor steering to compensate for platform roll). Adjacent altimeter swaths are overlapped cross-track by at least 50% to enable cross-calibration between swaths, consistency checks anywhere, and complete data coverage in case of data outages on single flight lines. Locations would emphasize tectonic plate boundaries (for fault zones and volcanoes) and coastlines, with access to international air space required for data collection. Data collection would consist of offset, parallel, overlapping flight tracks to build up a corridor of data covering the region of interest. There is no specific seasonal requirement, although for precise ground topographic mapping snow-free conditions are required and leaf-off conditions for areas of dense deciduous cover is preferred.

Communication needs such as real-time data or instrument control

- Primarily autonomous operation but periodic, over-the-horizon low rate communication for performance assessment and command/control. On-board intelligence with operational limits for instrument health and safety, as done for orbital instruments.

- Full rate data stored on board for retrieval at end of flights of hours duration. High-bandwidth data downlink for flights of days duration (Mbits/sec).

- Sensor web implementation to autonomously provide weather and cloud cover information to platform, which then optimizes flight path to acquire data in clearest areas.

<u>Mission Concept</u>: Describe in as much detail as possible the measurement approach:

Provide a narrative describing a “day-in-the-life” of the mission.

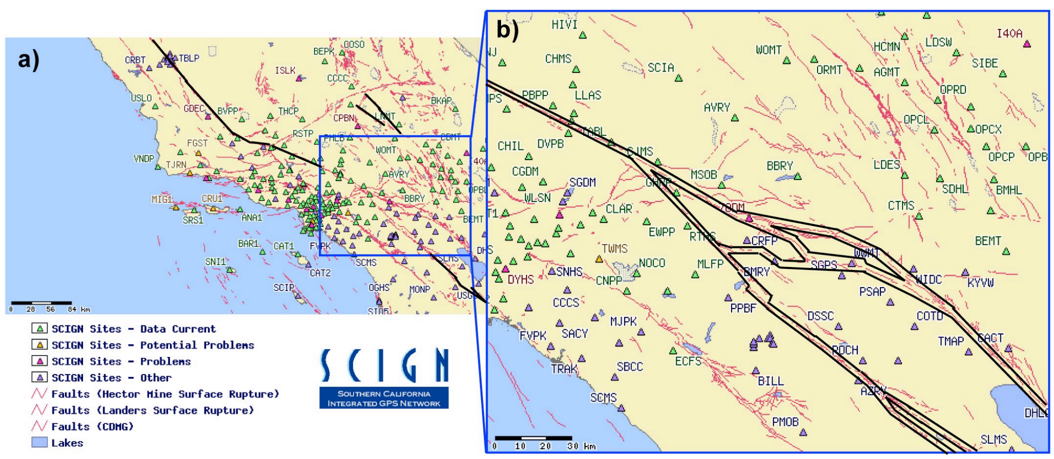
- Mission consist of two parts:
  (1) Comprehensive “baseline” mapping of areas likely to experience future surface deformation and topographic change due to natural hazard events (e.g. active fault zones and volcanoes, shorelines susceptible to storm surge flooding and erosion). This can be conducted over an extended period of time, as UAV assets are available. For specific areas of active faulting (e.g. southern California), total fault lengths of the order 1000 km would typically be mapped. The total data line length would depend on the number of overlapping swaths required to build up the necessary data corridor along the fault system. The required data corridor depends on the sinuosity and complexity of the fault zone and the expected width of surface deformation and topographic change of a magnitude large enough to be observed by this technique. Data line lengths of the order 10 times the fault zone length are likely given the assumed 3 km wide swath width and 50% sidelap.

  (1) Concentrated response mapping in areas where other observing capabilities indicate precursory surface deformation may be occurring

(e.g. volcano inflation indicating the potential for eruption) or where natural hazard events have occurred (e.g., earthquake, eruption, storm surge) to establish surface deformation and topographic change directly associated with the event (requiring deployment within hours to several days) and to observe transients following the event (continued for days to weeks). Typically fault lengths ruptured during a significant earthquake are of the order 100 km. Total data line lengths would depend on the number of overlapping swaths required to build up the necessary data corridor along the ruptured portion of the fault system.

Develop a diagram showing flight profile or maneuvers in time, space and/or geographic coordinates.

- Constant flight altitude, with corridors of data composed of overlapping flight swaths along relatively straights segments of fault zones or coastlines. An example of the comprehensive baseline mapping of corridors that might be done along selected southern California active faults (in red) is indicated in the figure by the black lines.



Identify any special or unique platform or mission issues

- As previously stated, precision knowledge of the aircraft flight path (5 cm) and sensor attitude (5 arc sec) are required post mission for processing of the data.

Summarize the key elements of the mission concept for this measurement.

- High spatial resolution (1 m), high vertical accuracy (0.1 m) observations of the ground surface, including where covered by vegetation, referenced to an absolute datum and repeated through time to observe surface deformation and topographic change achieved with a geodetic imaging lidar.

Earth Surface and Interior Structure – Gravitational Acceleration

<u>Critical Observation</u>: Gravitational Acceleration

<u>Observation / Measurement Definition</u>: Describe the phenomenon you want to observe. Describe what you need to measure.

- Gravitational acceleration is the acceleration due to mass attraction and varies spatially and temporally near Earth as a consequence of the inhomogeneity and the dynamics of Earth's mass density structure.
- Spatial variation occurs at all scales, from thousands of km, due to core/mantle boundary anomalies, to sub-kilometer and smaller, due to local topographic (or bathymetric) masses.

Explicitly state how this observation and measurement supports this Earth Science focus area.

- Earth's gravitational field defines satellite orbits, affects inertial navigation, reflects oil and mineral deposits, and characterizes crustal geologic structure. The equipotential surface, known as the geoid, defines a reference for sea surface topography (leading to oceanographic current determination through satellite ocean altimetry), and it defines the conventional reference of heights for national vertical geodetic control.
- The precise determination of the geopotential at global scales is sensitive to motion of oceanographic, hydrographic, and atmospheric masses. Its temporal variation at local and regional scales, reflecting mass motion at these scales, is potentially measurable with new-generation gravity gradiometers

Explicitly state the advantage of using a suborbital platform for this measurement.

- Moving-base gravitation measurement systems have been developed for satellites, aircraft, and ships. Satellite systems have global sensitivity and extent, but are limited in local resolution to scores of kilometers due to the ground-track speed of about 7 km/s. Moreover, the vertical attenuation of the field places severe sensor accuracy requirements on the system.
- Sub-orbital (i.e., aircraft) systems have higher resolution capability (kilometer and potentially sub-kilometer) that will not be attained by any satellite system in the foreseeable future, and they are somewhat less demanding in accuracy, but also more affected by the dynamics of the vehicle.
- Sub-orbital platforms have a large benefit-to-cost ratio, especially in remote and inaccessible regions of the world. This would even increase with less expensive vehicles (such as UAV's) that are remotely controlled and operated.

Earth Surface and Interior Structure – Gravitational Acceleration

Identify other cross-cutting areas impacted by this observation.

- Sub-orbital gravimetry systems complement and supplement satellite systems, by supporting validation and extending the resolution of sensors to the kilometer range. They are more readily combined with other solid Earth measurement systems, such as topographic mapping (SAR and Lidar) and magnetometry, for a comprehensive assessment and characterization of local and regional geophysics and geodynamics. Clear benefits include improved modeling of tectonics and associated volcanism and earthquake hazard zones.

Observation / Measurement System Requirements: Describe how you want to observe or measure the phenomena. Consider the following:

Instrument / Payload characteristics (type, weight, volume, environmental considerations, and access such as sampling or viewing ports)

- Gravimetry systems are based on two independent acceleration measurement systems: kinematic acceleration (typically derived from precise GPS positioning) and inertial acceleration, obtained from accelerometers (or gravimeters). GPS is now a given utility on any moving-base science platform and thus does not enter the instrument/payload characterization.
- Accelerometers require precise orientation with respect to inertial or navigation coordinate frames. This can be achieved by elaborate stabilized platforms, or mathematically with accurate sensing of the angular dynamics of the vehicle.
- Either mechanization requires some type of gyroscopes. Total vector gravimetry can be achieved with navigation-grade inertial navigation systems (produced by leading military and civilian avionics industry) that contain three accelerometers and three gyros.
- Such as system is totally autonomous, weighs about 20 lbs, occupies about 7” x 7” x 12” in volume with minimal clearance needed for heat dissipation, and consumes about 20 W (?) in power. Built for military applications, they have high environmental tolerances.
- Data interfaces and data logging equipment, currently, are not optimized for volume (typically based on desktop computers or laptop computer with docking station). Time synchronization with GPS time is critical and may be achieved with a built-in GPS receiver.
- These systems have been shown to yield precision in gravitation determination of a few parts in 10^6 with resolution of about 10 km (typical 100 m/s vehicle velocity).
- Other sensor options exist with varying capabilities. Current MEMS inertial measurement units are probably only marginally able to detect the un-modeled vertical gravitational component (at parts per 10^5). However, their volume, weight, and power consumption (?) are lower by a factor of 10. Dedicated airborne gravimeters yield the vertical component at 1-2 parts per 10^6, but are larger, heavier, and consume more power by a factor of 5 (?).

Earth Surface and Interior Structure – Gravitational Acceleration

- Gravimetry systems may also consist of acceleration gradiometers. In various design and development stages during the last four decades, gradiometers have only recently been put to use for geophysical survey operation, though only in a limited capacity due to their high cost ($2-3M). Their size, weight, and power consumption are comparable to airborne gravimeters (?). New technological developments (e.g., using atom interferometers) promise significant resolution enhancement and accuracy over current systems as well as accelerometer-based systems. Instrument characteristics for these are un-known at this time.

Flight characteristics (location, altitude, endurance, season, frequency). Discuss number of platforms, formation flying, or other special flight characteristics.

- Since gravimetry data need to be processed further using potential theory for geophysical interpretation, ideal surveys would yield regular, gridded data sets at constant altitude.
- Typically parallel straight tracks are surveyed with a number of cross track needed to remove between-track biases and trends. Track spacing should be comparable to along-track resolution (e.g., 10 km).
- Proximity to the mass anomalies enhances the signal-to noise ratio, therefore, low altitude is desirable (this may be offset by increased system error due to higher turbulence at lower altitude). Typical altitudes are 5000-10000 m.
- For strapdown inertial navigation systems and gravimeter systems, long (> 100 km), straight, and level tracks are preferred to minimize deleterious effects of aircraft dynamics associated with turns and accelerations in altitude.
- Repeat tracks (or multiple sensor systems) enhance ability to remove non-gravitational systematic errors.
- For accelerometer and gravimeter-based systems, continuous GPS visibility is required.
- Precision positioning (1 Hz, for kinematic acceleration determination) normally (currently) requires ground base station support (for differential phase data processing) not more than 100 km distant from vehicle.
- Geospatial registration (by GPS) is required to an accuracy of 3 m.

Communication needs such as real-time data or instrument control

- Real-time data transmission to base station is not required, since post-mission processing of data is the common application.
- Basic instrument requires data logging and data interface equipment.

Earth Surface and Interior Structure – Gravitational Acceleration

<u>Mission Concept</u>: Describe in as much detail as possible the measurement approach:

Provide a narrative describing a "day-in-the-life" of the mission.

- INS-based systems require a period (e.g., 5-7 minutes) of attitude initialization prior to take-off (this is done automatically by a navigation-grade INS; it could be done post-mission with MEMS IMU's).
- For UAV deployment, the vehicle would follow pre-programmed trajectories as described above.
- Tolerance on trajectories is estimated to be +/- 30 m (?).
- Upon the return of the vehicle to the base station, the data are downloaded and archived for later processing of the total mission.

Develop a diagram showing flight profile or maneuvers in time, space and/or geographic coordinates.

- Sample test surveys can be illustrated.

Identify any special or unique platform or mission issues

- See Observation / Measurement System Requirements

Summarize the key elements of the mission concept for this measurement.

- Using current INS technology requires precision GPS positioning and long, straight, level tracks. Typical surveys consist of multiple parallel tracks, but other sortie geometries might be considered (e.g., radial pattern from the center or from the circumference of a circle). Cross-tracks are essential to estimate relative biases and trends.

Earth Surface and Interior Structure – IPY Platform

Critical Observation: Low-altitude Surveying for Antarctic Exploration in the IPY

Observation / Measurement Definition: Describe the phenomenon you want to observe. Describe what you need to measure.

- Coordinated magnetometer, gravity, lidar measurements from a small, easily deployed autonomous low-cost vehicle. Basic mapping to determine ice sheet bed characteristics, and ice sheet elevation, examine the geologic controls on ice sheet dynamics.

Observation / Measurement System Requirements: Describe how you want to observe or measure the phenomena. Consider the following:

Instrument / Payload characteristics (type, weight, volume, environmental considerations, and access such as sampling or viewing ports)

- Lightweight compact vector or scalar magnetometer
- Strapdown gravity system
- Small lidar system

Flight characteristics (location, altitude, endurance, season, frequency). Discuss number of platforms, formation flying, or other special flight characteristics.

- Flight lines from the coast into the interior and cross over. Range of minimum 500 nm, deployment from ice breaker.

Communication needs such as real-time data or instrument control

- Low-data-rate telemetry

Mission Concept: Describe in as much detail as possible the measurement approach:

(no input)

Earth Surface and Interior Structure – Magnetic Fields

<u>Critical Observation</u>: Measure vector and tensor magnetic fields to support comprehensive magnetic field source models and isolate time-varying crustal field components

<u>Observation / Measurement Definition</u>: Describe the phenomenon you want to observe. Describe what you need to measure.

- The magnetic field spectrum is undersampled in the spatial wavelengths intermediate between the near-surface (up to 2 km) and satellite altitude (350-700 km). These measurements are critical to producing models that account for all sources of magnetic fields from crust to core.
- The simplest implementation is a calibrated vector magnetometer on a single UAV, to simultaneous measurements from coordinated platforms over a wide area to eliminate noise from external time-varying fields, to magnetic tensor measurements using four microUAVs flying in formation.
- Measurement of the tensor has the advantage of enabling direct measurement of currents within the volume of the measurement space defined by the sensor array.
- Gradient tensor measurements would further allow the separation of field sources.

Explicitly state how this observation and measurement supports this Earth Science focus area.

- This observation addresses the need to measure variations of the Earth's magnetic field to in support of studies of the magnetic field behavior, geophysical and tectonic processes in the crust, and highly time-varying fields due to piezoelectricity (stress induced), fluid flow and magma dynamics.

Explicitly state the advantage of using a suborbital platform for this measurement.

- The altitude range, system size and weight, and desired surveying characteristics needed for these measurements is best suited to a microUAV platform.

Identify other cross-cutting areas impacted by this observation.

- Atmospheric electricity, cloud microphysics, buried/submerged object detection.
- Highly complementary to gravity and surface deformation measurements for hazard detection.

Earth Surface and Interior Structure – Magnetic Fields

<u>Observation / Measurement System Requirements</u>: Describe how you want to observe or measure the phenomena. Consider the following:

Instrument / Payload characteristics (type, weight, volume, environmental considerations, and access such as sampling or viewing ports)

- Magnetometer <2000 g (with electronics), <1000 cm3, need magnetically quiet vehicle, and few arc-sec attitude knowledge at 1 Hz. Sampling at few Hz to 20 Hz.

Flight characteristics (location, altitude, endurance, season, frequency). Discuss number of platforms, formation flying, or other special flight characteristics.

- Single UAV flight altitude between few km up to 35 km. Long flight lines or grid surveys.
- Prefer night flying (quiet external fields environment).
- One-time survey (for combining satellite and surface data).
- Except for time-varying field monitoring, which could be done monthly to daily for high priority targets, and yearly or every several years for baseline time series.

Communication needs such as real-time data or instrument control

- Data volume is low, could be stored onboard.

Earth Surface and Interior Structure – Magnetic Fields

<u>Mission Concept</u>: Describe in as much detail as possible the measurement approach:

Provide a narrative describing a "day-in-the-life" of the mission.

- Launch single or fleet of UAVs
- Fly prescribed lines or grid survey
- Land and dump data or downlink during flight

- Formation:
  - Launch group of four UAVs and maintain formation with 100's of m to kms length separation baselines (to TBD separation accuracy) for length of flight.
  - No time constraint on completing a single survey.

- Could be combined with gravity and lidar

Develop a diagram showing flight profile or maneuvers in time, space and/or geographic coordinates.

(no input)

Identify any special or unique platform or mission issues

- Magnetically quiet vehicle

Summarize the key elements of the mission concept for this measurement.

- Fly microUAVs alone or in formation with calibrated vector instruments (including precise attitude knowledge)

- Fly baseline surveys and measure time-varying magnetic fields with frequent repeat surveying

Earth Surface and Interior Structure

Key Messages

Issues of Importance to the Earth Surface and Interior Focus Area:

1. UAV/OPV will provide high resolution continuous 4-D observations that will not be available from spaceborne platforms for 10-15 years minimum

2. Because of natural attenuation of geopotential fields, UAV's can provide high spatial and temporal resolution observations not possible with satellites. High altitude UAV measurements provide quiescent observations needed for ultra high sensitivity measurement of the gravity field and will fill spectral gaps between geopotential satellite observations and national and commercial near surface studies.

3. Reconfigurability and adaptability of UAV's to instruments is an important enabling feature such as in radar applications where aperture design is an issue.

Across Focus Areas

1. Access to international airspace (airspace of other nations) for UAVs is a critical issue-an argument for OPV availability in the near term.

2. Need OPV as transition to UAV for the development of instrument technology, exploration capability, and algorithms.

3. Readily accessible low cost UAV fleet will provide important and valuable development platforms for rapid concept development and testing.